High Luminosity LHC IR Quadrupole Development plan 2013-2016

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[Authors]

# 1. Background:

Following the July 2012 review of LARP, DOE has requested a plan for US contributions to the HighLuminosity LHC, which will be implemented through a construction project starting in 2017 and completed in 2022. A funding envelope of 200M$ was provided. The LARP note dated September 4 (by Prebys et al) defines a process to refine the cost estimates for potential US contributions and down-select a final list of deliverables for construction. It is expected that this list will include a significant portion (e.g. half) of the IR Quadrupole cold masses. DOE also requested that the LARP effort and organization is restructured to more directly support the needs of the construction project, and in particular to decrease the project risk. The magnet development plan presented by LARP at the DOE review included: completion of the quadrupole R&D (LQ, HQ and Long HQ models); design and fabrication of a 2 m model of the final design (SQXF) with first test in in 2015; and fabrication of a pre-series prototype (MQXF) to be completed in 2017. This plan assumed significant contributions by CERN and for the US-LARP part, required an increase of funding and resources by about a factor of 2 with respect to those currently allocated to the magnet systems effort.

Following the review, DOE provided the following feedback and guidance:

* Reduce the scope of the R&D portion of the LARP program, in particular the Long HQ models
* Increase the effort directed toward the 150 mm prototype, in particular by including in the plan a performance demonstrator of the final design (LQXF) with length of 3-4m, built primarily in the USwith a first test in the 2015 time frame
* Integrate additional resources from the GAD programs to help achieve the program goals

The revised plan is described in this document.

# 2. Main program components (goals, deliverables and schedule)

## 2.1 Conductor development

Up to now, two types of wire were used in LARP models, RRP 54/61 and RRP 108/127. The RRP 54/61 wire was produced with consistent properties and delivered solid performance allowing the LR, TQ and LQ models to reach their key performance goals. However, this design results in a rather large effective filament size leading to reduced stability margins which limited the 1.9 K performance of TQ and LQ models. The RRP 108/127 wire has smaller filaments and demonstrated very good properties and performance in the TQS03 models, leading to its adoption as a baseline LARP wire starting in 2009. However, production has not been consistent and in recent tests of HQ and LQ models RRP 108/127 has not reached the performance levels obtained with RRP 54/61. Finally, advanced designs using larger stacks are also under development and could potentially provide better performance, but there is limited time (~2 years) for incorporating these designs in the program.

Based on the above considerations, the following goals are proposed for conductor development:

* Demonstrate RRP 108/127 strand of 0.85 mm diameter which can be produced in large quantities consistently meeting the performance targets required for the construction project as set by LARP. Further discussion is required to set these targets, but we anticipate using as a reference the performance characteristics which were obtained in early procurements of this strand. A convincing demonstration would involve delivery of 5-10 billets consistently meeting LARP performance goals, and acceptance by OST of these targets as a specification for fixed price orders. Desired timeline: 2014
* Demonstrate the potential of 169 sub-element stack by delivering sufficient quantities of 0.85 mm wire for production of a few UL of SQXF cable, and fabrication of short coils for mirror tests. Timeline: 2014 (to allow characterization/demonstration in models on a time scale useful for making decisions for the construction project)
* Demonstrate the capability to scale-up production to larger billets (~60 kg). In principle, this should be done for both the 127 stack and the 169 stack (since both options are under consideration for production). It also appears that there could be some advantage in combining points (b) and (c) for the 169 stack (i.e. developing the 169 stack directly on large billets). Therefore, the details of the billet scale-up plan require further discussion. A convincing demonstration would involve delivery of conductor from large billets consistently meeting performance goals, and acceptance by OST of the use of large billets for fixed-price orders. Desired timeline: 2015
* Additional developments of interest include cost reduction measures (such as the use of type 2 niobium) and improved robustness (such as optimization of doping and barrier design). These could be pursued in parallel or combined with the ones above.

We propose that after further discussion and detailing of the plan, CDP resources are directed toward these tasks in support of LARP/HiLumi.

Note: while there is a strong interest in the development of the RRP 217 stack for future applications, it appears that this development is not compatible with the timeline of LARP/HiLumi and therefore it should be given lower priority over the next several years. This is however open for discussion.

## 2.2 Long Quadrupole – LQ

The Long Quadrupole program has completed a series of tests using RRP 54/61 conductor, surpassing its 200 T/m target gradient by about 10%. The last step involved fabrication and test of a model (LQS03) using RRP 108/127 strand, aimed at reproducing the results obtained in short models using the same conductor (240 T/m). A first test was performed and quickly surpassed the 200 T/m target. However, training was limited to about 208 T/m. Based on the above considerations, the following steps are foreseen:

* Optimize the mechanical assembly and establish good correlation between FEA models and strain gauge measurements, ensuring sufficient pre-load up to 240 T/m. This task may also incorporate the demonstration of pre-loading using 4 m long units (bladders and master keys)
* Test the revised model. Assuming basic performance goals are met, perform studies to determine quench protection limits, in particular in case of limited/no energy extraction and no inner layer heaters, as allowed by the experimental setup. In principle, one additional cycle of assembly and test should be sufficient and the LQ program could be completed in FY13. However, the schedule could be longer depending on results and the overall program priorities (e.g. availability of test facility).

We propose that the above tasks are assigned as follows:

* a: LBNL
* b: FNAL for test, FNAL+LBNL for analysis

## 2.3 High Field Quadrupole – HQ

The High Field Quadrupole program includes fabrication of short coils and assembly/test in both quadrupole and mirror configurations. A series of test using first-generation coils was carried out (HQ01 series) and three mirror tests were performed using special coils aimed at understanding and addressing the performance issues observed in the HQ01 models. Second-generation coils are being fabricated for the HQ02 series, however, various design and process changes were implemented along the way so these coils do not constitute a uniform and fully optimized set. A third series of coils (HQ03) is planned incorporating all new features and processes to validate them for use in the QXF prototypes. Examples include: provisions for longitudinal and azimuthal cable expansion during reaction; cored cables; braided insulation; insulating coatings for metallic parts; instrumentation and heater designs. HQ03 test goals include field quality studies with a uniform set of coils, mechanical assembly and pre-load windows, quench protection limits.

In parallel, additional special coils are also foreseen for testing in the mirror structure, in particular to explore quench protection limits and new conductor designs. In preparation for the use of mirror structures for these tests, as well as the LHQ and LQXF mirror tests, additional mechanical analysis and experimental feedback from dummy assemblies is also needed, in particular to improve the preload control and reduce training in the mirror structure.

Impregnation of two short coils with rad-hard epoxies (Matrimid and Cyanate ester) is also underway in preparation for a more expansive validation of these materials by the Long HQ program. The best candidate could be tested in the mirror structure. Finally, the HQ platform may be used to test the applicability of the BNL structure concept as well as the planned approach to longitudinal stacking of half-length coils in the final prototype.

Based on the above considerations, the following steps are foreseen:

* a. Assemble and test of HQ02 with coil design improvements (but not applied uniformly to all coils: Ta vs. Ti doping, sleeve/braid insulation, changes in heater design, coating of parts etc.)
  + Expect several cycles of assembly and test to fully understand and optimize mechanical assembly, field quality, quench protection etc.
  + Testing at CERN is foreseen, since it is the only facility providing 1.9 K capability. This however may be complemented by tests at other facilities depending on goals and turnaround time.
  + Timeline: Jan-Dec 2013
* b. Impregnation of dummy coil 18 and 19 with rad-had epoxies (timeline: mid-2013)
* c. Mechanical optimization of mirror structure (timeline: mid-2013)
* d. Test and analysis of mechanical model of BNL structure (timeline: 2012)
* e. HQ03: field quality with uniform coils incorporating all design improvements
  + Fabrication of 5-6 coils – cable and parts are available
  + Several cycles of assembly and test to fully understand and optimize mechanical assembly, field quality, quench protection etc.
  + Testing at CERN is foreseen, since it is the only facility providing 1.9K capability. This however may be complemented by tests at other facilities depending on goals and turnaround time.
  + Timeline: coil fabrication in 2013, testing in 2014
* f. Test of optimized coils in mirror structure, to verify mechanical improvements and perform studies of quench limits (timeline: 2013)
* g. Fabrication and test of special coils and test in mirror structure, to validate advanced conductor options such as RRP 169 and PIT (timeline: 2014)
* h. Design and fabrication of a 1 m long structure of the BNL design. Assembly with coils from HQ02 and test. Note: this task will proceed following (1) positive results from the 6’’ mechanical model, point d; (2) conceptual design studies showing the applicability and potential advantages with respect to the approach used in current models. Timeline: structure fabrication 2013-14; assembly and test 2014-15
* Optional test of double length configuration (1m+1m) if required by QXF (timeline: 2015-16). This test requires two sets of HQ coils, i.e. both HQ02 and HQ03.

We propose that the above tasks are assigned as follows:

* a: LARP+CERN
* b: LARP
* c: FNAL
* d: LARP
* e: LBNL+CERN
* f: FNAL
* g: LBNL (coil fabrication) and FNAL (mirror assembly and test)
* h: LARP
* i: LARP

## 2.4 Long High Field Quadrupole - LHQ

The revised LHQ program has a reduced scope that focuses on essential feedback relevant to the design of the 150 mm prototypes. In particular, LHQ provides an opportunity to demonstrate the use of 1-pass cored cables and braided insulation in long coils, and update the expansion parameters used to prevent excessive strain during reaction to these cables and insulation. In addition, it will confirm the validity and applicability in long coils of various new features designed to improve the electrical integrity of the coils.

For the near term, the LHQ platform also provides the best opportunity to determine the applicability of rad-hard epoxies for use in the upgraded quadrupoles. Long coils are required to provide a convincing demonstration due to the specific challenges of these systems, such as low pot life and the need to maintain strictly controlled elevated temperatures during the filling process. At this time, all tooling and parts for LHQ coils have been procured, along with a significant fraction of the superconducting cable. The LHQ mirror structure is based on the one used for LQ and HQ. It will require some additional parts and possible modifications based on improvements to the HQ mirror.

Based on the above considerations, the following steps are foreseen:

* Fabrication of 2 practice coils (timeline: 2013)
* Adaptation of the mirror structure to LHQ (time line: 2013)
* Fabrication of 1 regular (baseline) coil and test in mirror structure (timeline: 2013)
* Fabrication of 2-3 rad-hard coils and 1-2 tests in the mirror structure (timeline: 2014)

We propose that the above tasks are assigned as follows:

* a: LARP
* b: LARP
* c: FNAL (+ LARP)
* d: FNAL (+ LARP)

## 2.5 IR Quadrupole Performance Demonstrator - QXF

Goal of the QXF program is to demonstrate all key performance parameters (gradient, training, field quality, quench protection) required for the IR Quadrupoles, therefore validating the critical design choices (such as cable, cross-section, mechanical structure) and the fabrication/assembly procedures.

Two series of models are foreseen: a short model (SQXF) with a coil length of about 1.5 m, and along model (LQXF) with a coil length of about 3m. Both short and long models will proceed essentially in parallel aiming at first tests in 2015. The design for both SQXF and LQXF will be carried out by a joint LARP-CERN team in the frame of the Hi-Lumi LHC project (work package 3.2, IR quadrupoles) and will incorporate all known requirements for the final magnet. However, taking into account that a number of key interfaces will not be finalized until the TDR also planned for 2015, we should expect that an additional iteration will be made around 2016 to finalize the design of the pre-series prototype (MQXF), incorporating all the interfaces specified in the TDR and feedback from the SQXF and LQXF tests. Since the SQXF and LQXF models will proceed mostly in parallel, we will not get the full benefit of feedback from short model results to long model design. However, there will still be some opportunities for feedback from short models to long models at the level of individual operations (e.g. coil winding, etc.) After 2015, when both platforms will be available, it will be possible to optimize the program by assigning specific studies to short or long models as most appropriate. In addition, much useful information can be extracted by comparing the results from short and long models.

This strategy will require the short and long model programs to be very closely integrated. In terms of the general design, the integration will come from the Hi-Lumi project structure. Close attention by task managers will be required to ensure that consistent choices are made at the level of design details and fabrication processes. We will also look for opportunities to ensure uniformity at the level of individual components, for example by conducting combined procurements of parts and tooling for short and long models. The details of the QXF plan are still being developed. However, it was generally agreed that CERN will take primary responsibility for the short model, with significant contributions by LARP (e.g. fabrication of half of the coils). The long model will be under LARP responsibility and will be fabricated, assembled and tested mostly in the US, so that it can function as a demonstrator for the purpose of DOE project approval.

The following tasks and timeline will be assumed for the purpose of estimating LARP costs and resource requirements:

* Conceptual design and analysis (until March 2013)
* Design and procure 2 sets of (winding, curing, reaction, potting) tooling for long coils (Feb 2013 to March 2014)
* Procure 1 set of (winding, curing, reaction, potting) tooling for short coils (August 2013 to December 2013)
* Design and fabrication of mirror structure for short coils (April 2013 to April 2014)
* Design and fabrication of mirror structure for long coils (April 2013 to April 2014)
* Design and fabrication of mechanical structure for long models (April 2013 to April 2014)
* Mechanical model: assembly and cool-down of structure with dummy coils (October 2013 to September 2014)
* Cable, parts, labor for fabrication of 6 short coils January 2014 to June 2015)
* Assembly and test of 2 short mirrors (October 2014 to March 2015)
* Cable, parts and labor for fabrication of 2 long practice coils (April 2014 to October 2014)
* Cable, parts and labor for fabrication of 1 long coil for first mirror test (June 2014 to November 2014)
* Assembly and test of first mirror (November 2014 to March 2015)
* Cable, parts and labor for fabrication of 4 long coils for LQXF01 (July 2014 to April 2015)
* Assembly, test and disassembly of LQXF01 (April 2015 to September 2015)
* Assembly, test and disassembly of LQXF01b (September 2015 to February 2016)
* Cable, parts and labor for fabrication of 4 long coils for LQXF02 (December 2014 to November 2015)
* Assembly, test and disassembly of LQXF02 (February 2016 to July 2016)
* Assembly, test and disassembly of LQXF02b (August 2016 to December 2016)

# 3. Infrastructure upgrades

Infrastructure upgrades will be required for QXF (in particular to enable 1.9 Koperation and cope with the high stored energy levels during test) and to prepare the fabrication facilities for prototype and production phases. A combination of GAD resources, Laboratory infrastructure funds and DOE supplemental funds may be required to accomplish these tasks. Desired upgrades include:

## 3.1 Magnet test facility (FNAL)

• 1.9K operation, current leads, magnetic measurements, quench protection/extraction for QXF

## 3.2 Cabling facility (LBNL)

• Better QA, more efficient operation for fabrication of long lengths of cable

## 3.3 Winding machines (FNAL/BNL)

• Any refurbishing in view of prototype fabrication.

# 4. Pre-series prototype

The 150 mm pre-series prototype (MQXF) will require new coils and structure to account for the final length and design features. The design will need to incorporate feedback from LQXF, and the required interfaces will be defined by the HL-LHC TDR planned for 2015. Therefore, work on the prototype may start in 2016 and be completed in 2018.

From the above considerations, it is assumed that fabrication of the cold mass of the pre-series prototype will be part of the scope of the construction project. It is also assumed that the cryostat and integration task will be a CERN responsibility.

# 5. Organization

The LARP deliverables will be organized with the usual approach. A new branch of the WBS structure will be created for QXF, covering both the long models and the portion of the short model tasks performed in the US.

The GAD contributions will be organized by the respective PIs based on agreed upon documents specifying key goals and milestones. These documents should also specify in detail how GAD and LARP will share management responsibility for these deliverables. Somewhat different approaches might be chosen depending on the specific deliverable. Monthly progress reports will be produced for each deliverable. Periodical assessments on the status of the program and required revisions of the plan will be performed by a coordination board including representatives from LARP, GAD and Laboratory management